

Directed flow as a signal of a liquid state of transient matter

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Abstract

Directed flow v_1 , observable introduced for description of nucleus collisions is discussed. We consider a possible origin of the flow in hadronic reactions as a result of rotation of the transient matter and trace analogy with nucleus collisions. It is argued that the presence of directed flow can serve as a signal that transient matter is in a liquid state.

Introduction

The deconfined state of transient matter found in the four major experiments at RHIC [1] reveals the properties of the perfect liquid, being strongly interacting collective state and therefore it was labelled as sQGP [2]. The nature of new form of matter discovered is not known, many different interpretations were proposed for the explanations of the experimental findings. The utmost significance of these experimental discoveries lies in the fact that the matter is strongly correlated and reveals high degree of the coherence when it is well beyond the critical values of density and temperature.

Important tools in the studies of the nature of the new form of matter are the anisotropic flows which are the quantitative characteristics of the collective motion of the produced hadrons in the nuclear interactions. With their measurements one can obtain a valuable information on the early stages of reactions and observe signals of QGP formation.

In the same time, the measurements of anisotropic flows and constituent quark scaling demonstrated an importance of the constituent quarks [3] and their role as effective degrees of freedom of the newly discovered state of matter. Of course the dynamics of strong interactions is the same for the hadron and nucleus collisions, and therefore the following question naturally arises, namely, in what extent, if anything, the recent discoveries at RHIC relevant for hadronic interactions?

In this note we try to address in a model way one aspect of this broad problem, i.e. we discuss the role of the coherent rotation of the transient matter in hadron collisions as the origin of the directed flow in these reactions and stress that behavior of collective observable v_1 in hadronic and nuclear reactions would be similar and originates from the liquid state of transient matter.

The experimental probes of collective dynamics in AA interactions [3, 4], the momentum anisotropies v_n are defined by means of the Fourier expansion of the transverse momentum spectrum over the momentum azimuthal angle ϕ . The angle ϕ is the angle of the detected particle transverse momentum with respect to the reaction plane spanned by the collision axis z and the impact parameter vector \mathbf{b} directed along the x axis. Thus, the anisotropic flows are the azimuthal correlations with the reaction plane. In particular, the directed flow is defined as

$$v_1(p_\perp) \equiv \langle \cos \phi \rangle_{p_\perp} = \langle p_x / p_\perp \rangle = \langle \hat{\mathbf{b}} \cdot \mathbf{p}_\perp / p_\perp \rangle \quad (1)$$

From Eq. (1) it is evident that this observable can be used for studies of multiparticle production dynamics in hadronic collisions provided that impact parameter \mathbf{b} is fixed. Therefore we discuss hereabout directed flow v_1 in hadron collisions at fixed impact parameters and refer after that those considerations to the collisions of nuclei keeping in mind the same nature of the transient states in both cases. We amend the model [5, 6] developed for hadron interactions (based on

the chiral quark model ideas) and consider the effect of collective rotation of a quark matter in the overlap region. We formulate a hypothesis on connection of the strongly interacting transient matter rotation with the directed flow generation.

1 Effective degrees of freedom and transient state of matter in hadron collisions

We assume that the origin of the transient state and its dynamics along with hadron structure can be related to the mechanism of spontaneous chiral symmetry breaking (χ SB) in QCD [7], which leads to the generation of quark masses and appearance of quark condensates. This mechanism describes transition of the current into constituent quarks. The gluon field is considered to be responsible for providing quarks with masses and its internal structure through the instanton mechanism of the spontaneous chiral symmetry breaking. Massive constituent quarks appear as quasiparticles, i.e. current quarks and the surrounding clouds of quark–antiquark pairs which consist of a mixture of quarks of the different flavors. Quark radii are determined by the radii of the surrounding clouds. Quantum numbers of the constituent quarks are the same as the quantum numbers of current quarks due to conservation of the corresponding currents in QCD.

Collective excitations of the condensate are the Goldstone bosons and the constituent quarks interact via exchange of the Goldstone bosons; this interaction is mainly due to pion field. Pions themselves are the bound states of massive quarks. The interaction responsible for quark-pion interaction can be written in the form [8]:

$$\mathcal{L}_I = \bar{Q}[i\partial - M \exp(i\gamma_5 \pi^A \lambda^A / F_\pi)]Q, \quad \pi^A = \pi, K, \eta. \quad (2)$$

The interaction is strong, the corresponding coupling constant is about 4. The general form of the total effective Lagrangian ($\mathcal{L}_{QCD} \rightarrow \mathcal{L}_{eff}$) relevant for description of the non-perturbative phase of QCD includes the three terms [9]

$$\mathcal{L}_{eff} = \mathcal{L}_\chi + \mathcal{L}_I + \mathcal{L}_C.$$

Here \mathcal{L}_χ is responsible for the spontaneous chiral symmetry breaking and turns on first.

To account for the constituent quark interaction and confinement the terms \mathcal{L}_I and \mathcal{L}_C are introduced. The \mathcal{L}_I and \mathcal{L}_C do not affect the internal structure of the constituent quarks.

The picture of a hadron consisting of constituent quarks embedded into quark condensate implies that overlapping and interaction of peripheral clouds occur at the first stage of hadron interaction. The interaction of the condensate clouds assumed to be of the shock-wave type, this condensate clouds interaction generates the

quark-pion transient state. This mechanism is inspired by the shock-wave production process proposed by Heisenberg [10] long time ago. At this stage, part of the effective lagrangian \mathcal{L}_C is turned off (it is turned on again in the final stage of the reaction). Nonlinear field couplings transform then the kinetic energy to internal energy [10, 11]. As a result the massive virtual quarks appear in the overlapping region and transient state of matter is generated. This state consist of $\bar{Q}Q$ pairs and pions strongly interacting with quarks. This picture of quark-pion interaction can be considered as an origin for percolation mechanism of deconfinement resulting in the liquid nature of transient matter [12].

Part of hadron energy carried by the outer condensate clouds being released in the overlap region goes to generation of massive quarks interacting by pion exchange and their number was estimated as follows as follows:

$$\tilde{N}(s, b) \propto \frac{(1 - \langle k_Q \rangle) \sqrt{s}}{m_Q} D_c^{h_1} \otimes D_c^{h_2} \equiv N_0(s) D_C(b), \quad (3)$$

where m_Q – constituent quark mass, $\langle k_Q \rangle$ – average fraction of hadron energy carried by the constituent valence quarks. Function D_c^h describes condensate distribution inside the hadron h and b is an impact parameter of the colliding hadrons. Thus, $\tilde{N}(s, b)$ quarks appear in addition to $N = n_{h_1} + n_{h_2}$ valence quarks.

The generation time of the transient state Δt_{tsq} in this picture obeys to the inequality

$$\Delta t_{tsq} \ll \Delta t_{int},$$

where Δt_{int} is the total interaction time. The newly generated massive virtual quarks play a role of scatterers for the valence quarks in elastic scattering; those quarks are transient ones in this process: they are transformed back into the condensates of the final hadrons.

Under construction of the model for elastic scattering [5] it was assumed that the valence quarks located in the central part of a hadron are scattered in a quasi-independent way off the transient state with interaction radius of valence quark determined by its inverse mass:

$$R_Q = \kappa/m_Q. \quad (4)$$

The elastic scattering S -matrix in the impact parameter representation is written in the model in the form of linear fractional transform:

$$S(s, b) = \frac{1 + iU(s, b)}{1 - iU(s, b)}, \quad (5)$$

where $U(s, b)$ is the generalized reaction matrix, which is considered to be an input dynamical quantity similar to an input Born amplitude and related to the

elastic scattering scattering amplitude through an algebraic equation which enables one to restore unitarity [13]. The function $U(s, b)$ is chosen in the model as a product of the averaged quark amplitudes

$$U(s, b) = \prod_{Q=1}^N \langle f_Q(s, b) \rangle \quad (6)$$

in accordance with assumed quasi-independent nature of the valence quark scattering. The essential point here is the rise with energy of the number of the scatterers like \sqrt{s} . The b -dependence of the function $\langle f_Q \rangle$ has a simple form $\langle f_Q(b) \rangle \propto \exp(-m_Q b/\xi)$.

These notions can be extended to particle production with account of the geometry of the overlap region and properties of the liquid transient state. Valence constituent quarks would excite a part of the cloud of the virtual massive quarks and those quark droplets will subsequently hadronize and form the multiparticle final state. This mechanism can be relevant for the region of moderate transverse momenta while the region of high transverse momenta should be described by the excitation of the constituent quarks themselves and application of the perturbative QCD to the parton structure of the constituent quark. The model allow to describe elastic scattering and the main features of multiparticle production [5, 6, 14]. In particular, it leads to asymptotical dependencies

$$\sigma_{tot,el} \sim \ln^2 s, \quad \sigma_{inel} \sim \ln s, \quad \bar{n} \sim s^\delta. \quad (7)$$

Inclusive cross-section for unpolarized particles integrated over impact parameter \mathbf{b} , does not depend on the azimuthal angle of the detected particle transverse momentum. The s -channel unitarity for the inclusive cross-section could be accounted for by the following representation

$$\frac{d\sigma}{d\xi} = 4 \int_0^\infty d\mathbf{b} \frac{I(s, \mathbf{b}, \xi)}{|1 - iU(s, \mathbf{b})|^2}. \quad (8)$$

The set of kinematic variables denoted by ξ describes the state of the detected particle. The function I is constructed from the multiparticle analogs U_n of the function U and is in fact an non-unitarized inclusive cross-section in the impact parameter space and unitarity corrections is given by the factor

$$w(s, b) \equiv |1 - iU(s, b)|^{-2}$$

in Eq. (8). Unitarity modifies anisotropic flows. When the impact parameter vector \mathbf{b} and transverse momentum \mathbf{p}_\perp of the detected particle are fixed, the function $I = \sum_{n \geq 3} I_n$, where n denotes a number of particles in the final state, depends on

the azimuthal angle ϕ between vectors \mathbf{b} and \mathbf{p}_\perp . It should be noted that the impact parameter \mathbf{b} is the variable conjugated to the transferred momentum $\mathbf{q} \equiv \mathbf{p}'_a - \mathbf{p}_a$ between two incident channels which describe production processes of the same final multiparticle state. The dependence on the azimuthal angle ϕ can be written in explicit form through the Fourier series expansion

$$I(s, \mathbf{b}, y, \mathbf{p}_\perp) = I_0(s, b, y, p_\perp) \left[1 + \sum_{n=1}^{\infty} 2\bar{v}_n(s, b, y, p_\perp) \cos n\phi \right]. \quad (9)$$

The function $I_0(s, b, \xi)$ satisfies to the following sum rule

$$\int I_0(s, b, y, p_\perp) p_\perp dp_\perp dy = \bar{n}(s, b) \text{Im} U(s, b), \quad (10)$$

where $\bar{n}(s, b)$ is the mean multiplicity depending on impact parameter. The “bare” flow \bar{v}_n is related to the measured flow v_n as follows

$$v_n(s, b, y, p_\perp) = w(s, b) \bar{v}_n(s, b, y, p_\perp).$$

In the above formulas the variable y denotes rapidity, i.e. $y = \sinh^{-1}(p/m)$, where p is a longitudinal momentum. Evidently, corrections due to unitarity are mostly important at small impact parameters, i.e. they provide an additional suppression of the anisotropic flows at small centralities, while very peripheral collisions are not affected by these corrections.

The geometrical picture of hadron collision at non-zero impact parameters described above implies that the generated massive virtual quarks in overlap region will obtain large initial orbital angular momentum at high energies. The total orbital angular momentum can be estimated as follows

$$L(s, b) \simeq \alpha b \frac{\sqrt{s}}{2} D_C(b). \quad (11)$$

The parameter α is related to the fraction of the initial energy carried by the condensate clouds which goes to rotation of the quark system and the overlap region, which is described by the function $D_C(b)$, has an ellipsoidal form (Fig. 1). It should be noted that $L \rightarrow 0$ at $b \rightarrow \infty$ and $L = 0$ at $b = 0$ (Fig. 2).

2 Rotating transient matter and directed flow in hadronic reactions

Now we would like to discuss the experimental consequences of the described picture of hadron collisions. The important problem here is the experimental determination of the impact parameter \mathbf{b} . To proceed that way the measurements of

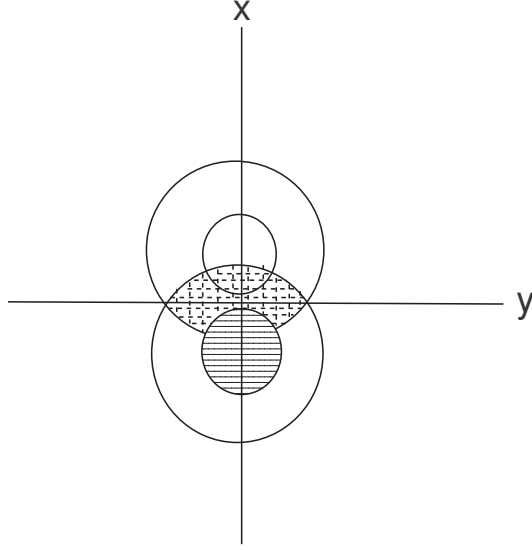


Figure 1: Schematic view in frontal plane of the hadron collision as extended objects. Collision occurs along the z-axis.

the characteristics of multiparticle production processes in hadronic collisions at fixed impact parameter should be performed with selection of the specific events sensitive to the value and direction of impact parameter. The determination of the reaction plane in the non-central hadronic collisions could be experimentally realizable with the utilization of the standard procedure [15, 16]. The relationship of the impact parameter with the final state multiplicity is a useful tool in these studies similar to the studies of the nuclei interactions. For example, in the Chou-Yang geometrical approach [17] one can restore the values of impact parameter from the charged particle multiplicity [18]. The centrality is determined by the fraction of the events with the largest number of produced particles which are registered by detectors (cf. [19]). Thus, the impact parameter can be determined through the centrality and then, e.g. directed flow, can be analyzed by selecting events in a specific centrality ranges. Indeed, the relation

$$c(N) \simeq \frac{\pi b^2(N)}{\sigma_{inel}}, \quad (12)$$

between centrality and impact parameter was obtained [20] and can be extended straightforwardly to the case of hadron scattering. In this case we should consider \bar{R} as a sum of the two radii of colliding hadrons and σ_{inel} as the total inelastic hadron-hadron cross-section. The centrality $c(N)$ is the centrality of the events with the multiplicity larger than N and $b(N)$ is the impact parameter where the mean multiplicity $\bar{n}(b)$ is equal to N .

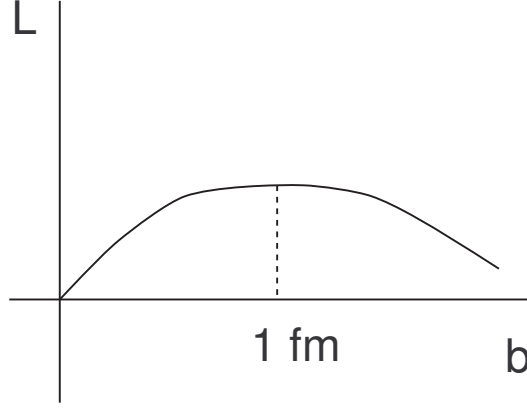


Figure 2: Qualitative dependence of the orbital angular momentum L on the impact parameter b .

At this point we would like to stress again on the liquid nature of transient state. Namely due to strong interaction between quarks in the transient state, it can be described as a quark-pion liquid. Therefore, the orbital angular momentum L should be realized as a coherent rotation of the quark-pion liquid as a whole in the xz -plane (due to mentioned strong correlations between particles presented in the liquid). It should be noted that for the given value of the orbital angular momentum L kinetic energy has a minimal value if all parts of liquid rotates with the same angular velocity. We assume therefore that the different parts of the quark-pion liquid in the overlap region indeed have the same angular velocity ω . In this model spin of the polarized hadrons has its origin in the rotation of matter hadrons consist of. In contrast, we assume rotation of the matter during intermediate, transient state of hadronic interaction.

Collective rotation of the strongly interacting system of the massive constituent quarks and pions is the main point of the proposed mechanism of the directed flow generation in hadronic and nuclei collisions. We concentrate on the effects of this rotation and consider directed flow for the constituent quarks supposing that directed flow for hadrons is close to the directed flow for the constituent quarks at least qualitatively.

The assumed particle production mechanism at moderate transverse momenta is an excitation of a part of the rotating transient state of massive constituent quarks (interacting by pion exchanges) by the one of the valence constituent quarks with subsequent hadronization of the quark-pion liquid droplets. Due to the fact that the transient matter is strongly interacting, the excited parts should be located closely to the periphery of the rotating transient state otherwise absorption would not allow to quarks and pions to leave the region (quenching). The mech-

anism is sensitive to the particular rotation direction and the directed flow should have opposite signs for the particles in the fragmentation regions of the projectile and target respectively. It is evident that the effect of rotation (shift in p_x value) is most significant in the peripheral part of the rotating quark-pion liquid and is to be weaker in the less peripheral regions (rotation with the same angular velocity ω), i.e. the directed flow v_1 (averaged over all transverse momenta) should be proportional to the inverse depth Δl where the excitation of the rotating quark-pion liquid takes place (Fig. 3) i.e.

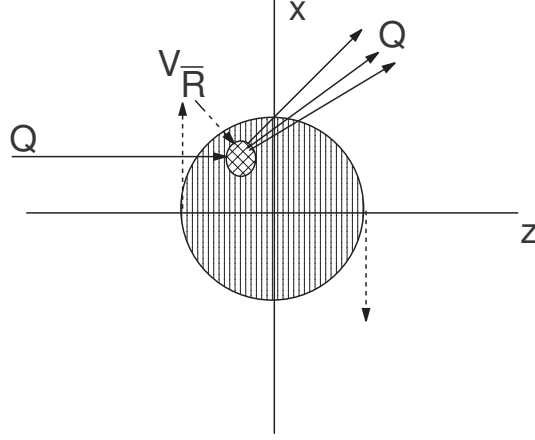


Figure 3: Interaction of the constituent quark with rotating quark-pion liquid.

$$|v_1| \sim \frac{1}{\Delta l} \quad (13)$$

In its turn, the length Δl is related to the energy loss of constituent valence quark in the medium due to elastic rescattering (quark-pion liquid) prior an excitation occurs, i.e. before constituent quark would deposit its energy into the energy of the excited quarks (those quarks lead to the production of the secondary particles), i.e. it can be assumed that

$$\Delta l \sim \Delta y,$$

where $\Delta y = |y - y_{beam}|$ is the difference between the rapidities of the final particle and the projectile. On the other hand, the depth length Δl is determined by elastic quark scattering cross-section σ and quark-pion liquid density n . Therefore, the averaged value of v_1 should be proportional to the particle density of the transient state and include cross-section σ , i.e.

$$\langle |v_1| \rangle \sim \sigma n. \quad (14)$$

This estimate shows that the magnitude of the directed flow could provide information on the properties of the transient state. The magnitude of observable v_1

(determined by the shift of transverse momentum due to rotation) is proportional to $(\Delta l)^{-1}$ in this mechanism and depends on the rapidity difference as

$$|v_1| \sim \frac{1}{|y - y_{beam}|} \quad (15)$$

and does not depend on the incident energy. Evidently, the directed flow $|v_1|$ decreases when the absolute value of the above difference increases, i.e. $|v_1|$ increases at fixed energy and increasing rapidity of final particle and it decreases at fixed rapidity of final particle and increasing beam energy. Dependence of $|v_1|$ will be universal for different energies when plotted against the difference $|y - y_{beam}|$ (Fig.4).

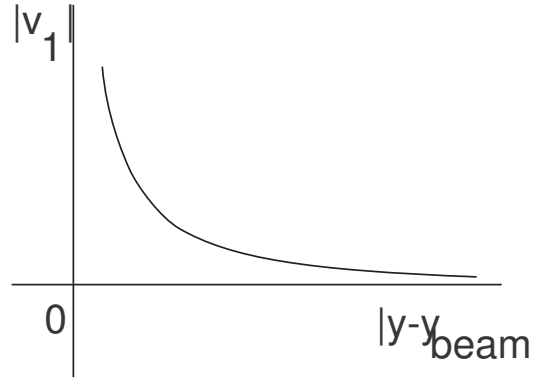


Figure 4: Universal dependence of directed flow on the rapidity difference.

The centrality dependence of $|v_1|$ is determined by the orbital momentum dependence L on the impact parameter, i.e. it should be decreasing towards high and lower centralities. Decrease toward high centralities is evident, no overlap of hadrons or nuclei should be at high enough impact parameters. Decrease of v_1 toward lower centralities is specific prediction of the proposed mechanism based on rotation since central collisions with smaller impact parameters would lead to slower rotation or its complete absence in the head-on collisions¹. Thus, the qualitative centrality dependence of $|v_1|$ corresponds to Fig. 2.

Now we can consider transverse momentum dependence of the directed flow $v_1(p_\perp)$ (integrated over rapidity) for constituent quarks. It is natural to suppose that the size of the region where the virtual massive quark Q comes from the quark-pion liquid is determined by its transverse momentum, i.e. $\bar{R} \simeq 1/p_\perp$. However, it is evident that \bar{R} should not be larger than the interaction radius of

¹Of course, there is another reason for vanishing v_1 at $b = 0$, it is rotational invariance around collision axis.

the valence constituent quark R_Q (interacting with the quarks and pions from the transient liquid state). The production processes with high transverse momentum such that \bar{R} is much less than the geometrical size of the valence constituent quark r_Q resolve its internal structure as a cluster of the non-interacting partons. Thus, at high transverse momenta the constituent quarks will be excited themselves and hadronization of the uncorrelated partons would lead to the secondary particles with high transverse momenta and vanishing directed flow. If the production mechanism rendering to the constituent quark excitation is valid, then similar conclusions on the small anisotropic flows at large transverse momenta should be applicable for $v_n(p_\perp)$ with $n > 1$. Obviously, it should not be valid in the case of the polarized hadron collisions.

The magnitude of the quark interaction radius R_Q can be taken from the analysis of elastic scattering [5]; it has dependence on its mass in the form (4) with $\kappa \simeq 2$, i.e. $R_Q \simeq 1 \text{ fm}^2$, while the geometrical radius of quark r_Q is about 0.2 fm . The size of the region³, which is responsible for the small- p_\perp hadron production, is large, valence constituent quark excites rotating cloud of quarks with various values and directions of their momenta in that case. Effect of rotation will be averaged over the volume $V_{\bar{R}}$ and therefore $\langle \Delta p_x \rangle_{V_{\bar{R}}}$ and $v_1(p_\perp)$ should be small.

When we proceed to the region of higher values of p_\perp^Q , the radius \bar{R} is decreasing and the effect of rotation becomes more prominent, valence quark excites now the region where most of the quarks move coherently in the same direction with approximately equal velocities. The mean value $\langle \Delta p_x \rangle_{V_{\bar{R}}}$ and the directed flow, respectively, can have a significant magnitude and increase with increasing p_\perp . When \bar{R} becomes smaller than the geometrical radius of constituent quark, the interactions at short distances start to resolve its internal structure as an uncorrelated cloud of partons. The production of the hadrons at such high values of transverse momenta is due to the excitation of the constituent quarks themselves and subsequent hadronization of the partons. The collective effects of rotating transient cloud in v_1 at large $p_\perp^Q > 1/r_Q$ will disappear as well as the directed flow of final particles. The value of transverse momentum, where the maximal values in the p_\perp -dependence of v_1 are expected, are in the region $1 \text{ GeV}/c$ since $r_Q \simeq 0.2 \text{ fm}$. The qualitative p_\perp -dependence of the directed flow is illustrated on Fig. 5.

3 Directed flow in nucleus collisions

Until now we considered hadron scattering and directed flow in this process, but significant ingredient in this consideration was borrowed from the AA studies,

²This is the light constituent quark interaction radius which is close to the inverse pion mass.

³For simplicity we suppose that this region has a spherically symmetrical form

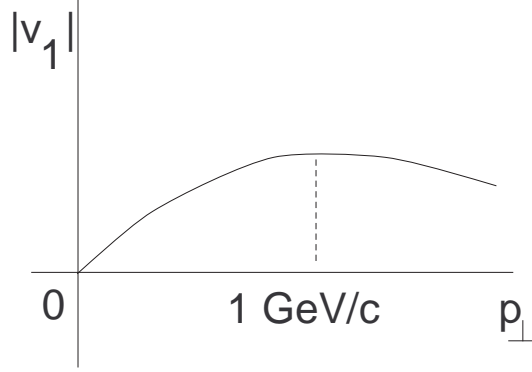


Figure 5: Qualitative dependence of directed flow on transverse momentum p_{\perp} .

namely we supposed that the transient matter is a strongly interacting one and it is the same in pp and AA reactions. Using the experimental findings of RHIC, we assumed, in fact, that it is a liquid consisting of massive quarks, interacting by pion exchange, and characterized by the fixed interparticle distances determined by the quark interaction radius. The assumption on the almost instantaneous, shock-wave type of generation of the transient state obtains then support in the very short thermalization time revealed in heavy-ion collisions at RHIC [21]. Existence of the massive quark matter in the stage preceding hadronization seems to be supported also by the experimental data obtained at CERN SPS [22].

The geometrical picture of hadron collision has an apparent analogy with collisions of nuclei and it should be noted that the appearance of large orbital angular momentum should be expected in the overlap region in the non-central nuclei collisions. And then due to strongly interacting nature of the transient matter we assume that this orbital angular momentum realized as a coherent rotation of liquid. Thus, it seems that underlying dynamics could be similar to the dynamics of the directed flow in hadron collisions.

We can go further and extend the production mechanism from hadron to nucleus case also. This extension cannot be straightforward. First, there will be no unitarity corrections for the anisotropic flows and instead of valence constituent quarks, as a projectile we should consider nucleons, which would excite rotating quark liquid. Of course, those differences will result in significantly higher values of directed flow. But, the general trends in its dependence on the collision energy, rapidity of the detected particle and transverse momentum, should be the same. In particular, the directed flow in nuclei collisions as well as in hadron reactions will depend on the rapidity difference $y - y_{beam}$ and not on the incident energy. The mechanism therefore can provide a qualitative explanation of the incident-energy scaling of v_1 observed at RHIC [23]. In the projectile frame the directed flow has

the same values for the different initial energies. In the Fig. 6 experimental data are shown along with the dependence

$$v_1 \sim (\eta - y_{beam})^{-1}, \quad (16)$$

where η is a pseudorapidity. This dependence reflects the trend in the experimental data and, therefore, the mechanism described in the previous section obtains an experimental justification, qualitative, of course. In addition, we would like to

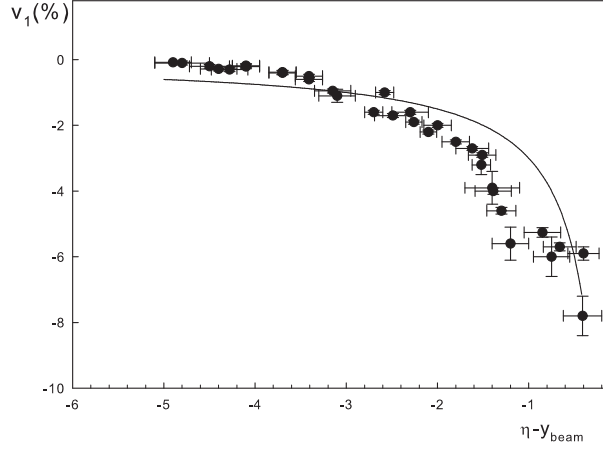


Figure 6: Dependence of directed flow on $\eta - y_{beam}$ in $Au + Au$ and $Cu + Cu$ collisions at 62.4 GeV and 200 GeV at RHIC (preliminary data of STAR Collaboration [23])

note that azimuthal dependence of the suppression factor R_{AA} found in the experiment PHENIX at RHIC [24] can also be explained by rotation of the transient state. Since the correlations result from the rotation in this mechanism and therefore are maximal in the rotation plane, similar dependence should be observed in the azimuthal dependence of the two-particle correlation function. Effect of rotation should be maximal for the peripheral collisions and therefore the dependence on ϕ should be most steep at larger impact parameter (or centrality) values. The discussed rotation mechanism should contribute to the elliptic flow too. However, since the regularities already found experimentally for v_1 and v_2 in nuclei interactions imply different dynamical origin for these flows, we should conclude that this mechanism does not provide significant contribution to the elliptic flow.

4 Directed flow at the NICA and LHC energies and conclusion

Nowadays, with approaching start of the LHC, and planning of NICA Project at JINR, Dubna it is interesting to predict what should be expected at such energies [25],[26] in particular would deconfined matter produced in pp and AA collisions be weakly interacting or it will remain to be a strongly interacting one as it was observed at RHIC in AA collisions? In the latter case one can expect that proposed rotating mechanism will be working at the LHC energies and in NICA and therefore the observed at RHIC incident-energy scaling in v_1 will remain to be valid also, i.e. directed flow plotted against the difference $y - y_{beam}$ will be the same as it is at RHIC. However, if the transient matter at the LHC energies or at NICA will be weakly interacting, then one should expect absence of the coherent rotation and the vanishing of the directed flow. This conclusion is valid provided that the rotation is the only mechanism of the directed flow generation. If it is so, vanishing directed flow can serve as a signal of a genuine quark-gluon plasma (gas of free quarks and gluons) formation.

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